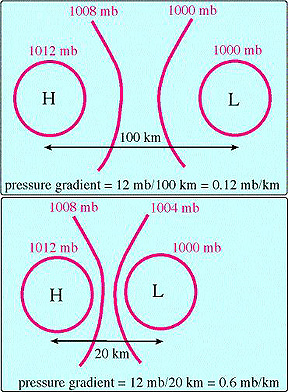
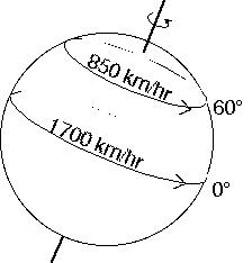
**ATMOSPHERIC CIRCULATION; WEATHER SYSTEMS.**

We are now ready to extend our understanding of air parcel and air mass movements to regional and global scales. As generalities: Air moves along pressure gradients from conditions of high pressure to lower pressure; warm air rises, cold air sinks; movements of air are influenced also by the motion of the Earth itself, as well as other forces.

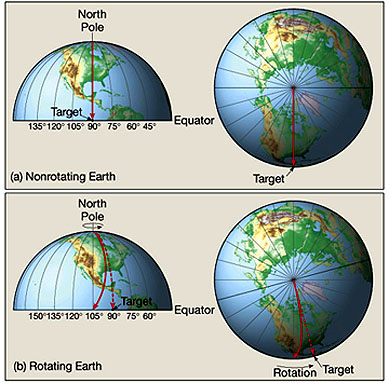
The dominant cause behind movement of air in near horizontal conditions is the pressure gradient. As seen in this diagram, if a high is next to a low and the rate of pressure drop, as indicated by the spacing of isobars (lines of equal pressure) of different values, is fairly wide, the pressure gradient is small so that the wind moving towards the low moves more slowly than when the isobars are close-spaced (higher gradient and faster wind flow).



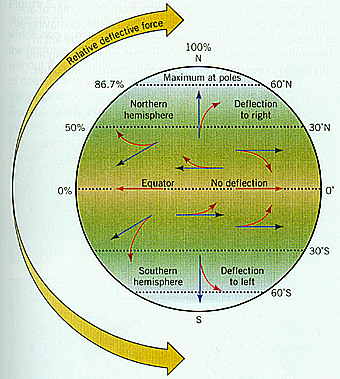
Lets switch to the last idea in the first paragraph: The Earth is spinning on its rotational axis at a rate approximating 1700 kilometers per hour (1062 mph). The speed diminishes poleward, going to just above zero immediately beyond the point where the axis can be imagined to emerge at the surface. This is indicated in the following diagram.



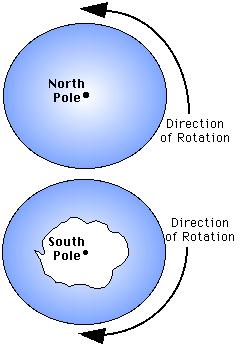
The differential velocities associated with the spin give rise to an effect on the air known as the **Coriolis Force**. Not a directly applied force as such, it nevertheless acts on moving air to deflect their paths in a systematic manner. As shown in the next figure, applicable to the northern hemisphere, air moving from a high pressure zone around the poles to lower pressures at the equator would move in a straight line if there were no rotation. But because of the rotation, the air moves to the right of its straight path as it moves equatorward. Think of it this way: As free flowing air just above the surface moves south over a short (finite) time span, the Earth underneath is moving counterclockwise; points to the west of the intended path, if non-rotational, move eastward as the motion progresses. At lower latitudes points further and further west move to meet the intended path; tracing this out over time yields a curving line that has an apparent deflection pathway to the right (this has an analogy of crosswind in a baseball stadium causing a fly ball to curve in response).



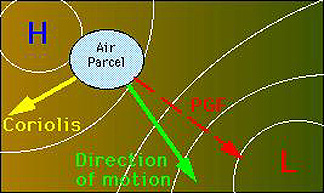
Consider this diagram (about which more will be introduced later on this page). Blue arrows denote a possible straight line path. Red arrows indicate the Coriolus-induced deflections.These are to the right in the northern hemisphere and to the left in the southern hemisphere.



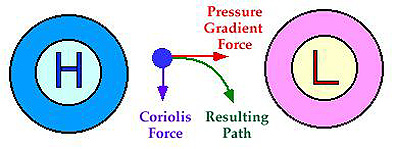
The reason for the reversal - right or left - is just the consequence of direction of motion in the two hemispheres. This next diagram explains that statement. Those in the southern hemisphere are in a sense upside down relative to those in the north so the perception of motions is reversed.



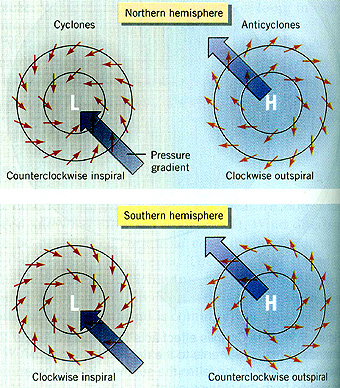
The basic idea behind the Coriolis effect is that the resultant wind direction is a product of two competing forces. In the diagram here, the Pressure Gradient Force PGF (from high to low) is acting in a North-South direction and the Coriolis Force (not as strong) in a West to East direction. The Net Direction of Motion is the resultant of vector addition of the two forces in the previous sentence.



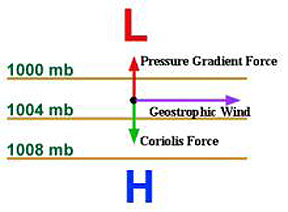
The next diagram further elucidates the Coriolis idea. As one looks down on a (circular) high pressure air mass, two forces are assumed to be acting on associated winds - the PGF moving from higher to lower pressure states and the Coriolis force (CF) in the northern hemisphere. The resultant curving path is shown in green.



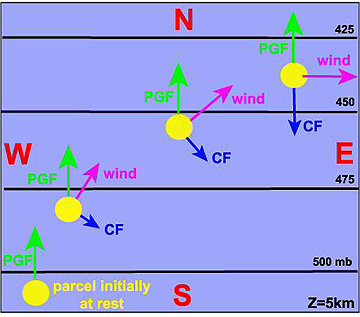
Lets summarize this concept for both terrestrial hemispheres:



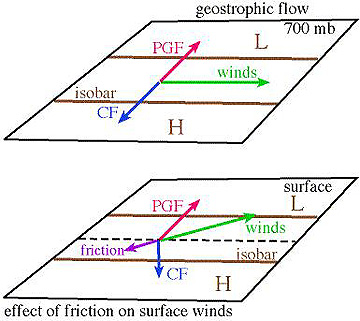
We'll consider at this point another idea that depends on the Coriolis force. The Geostrophic Wind is a special case in which rising air reaches a condition of balanced forces such that the wind flow becomes parallel to an *isobar* - which is a line on a plot of air pressures relative to the surface which connects points representing the lateral extent of air having the same pressure (analogous to a contour line on a topographic map [recall Section 10]). The first diagram is a simplified map of the forces involved relative to an isobar; the second diagram shows the changes in wind direction with height until the geostrophic condition is met. Geostrophic winds are real and do happen but most of the time winds are not parallel to isobars.



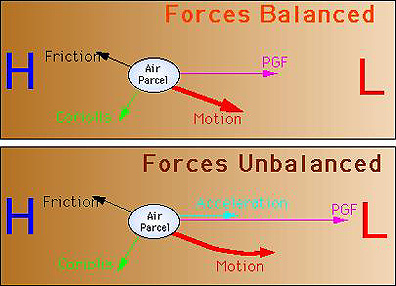
This diagram shows how a moving air parcel moves obliquely across a pressure gradient and rotates until its winds become geostrophic.



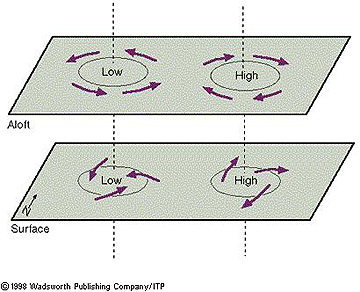
Near the Earth's surface, friction of moving wind across terrain or open water becomes a factor. Here the resultant wind direction is a vectorial sum of the PGF, CF, and FF (frictional force). At some altitude, where friction is nil, in this case a geostrophic wind has evolved.



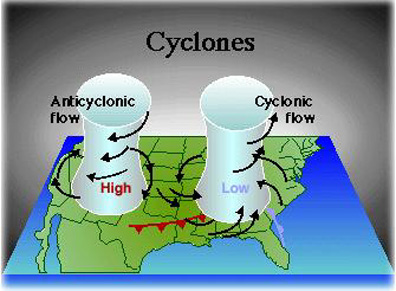
We all know from countless experiences that winds vary in velocity. Gentle breezes move at rates of only a few kilometers per hour. A wind moving at 30 kph is considered strong. When speeds reach above 70 kph, the winds are of hurricane force. (In a storm, wind changes directions and speeds frequently change in different places and times owing to local variations in pressure gradients and friction in part because of obstructions and surface topographic fluctuations.) One cause of change in wind speed is that of unbalanced forces. In the diagram below, the PGF is strong enough to counter-influence the CF and FF such that the net wind experiences an acceleration.



Assuming the ideal case in which isobars are closed and circular, the patterns of wind flow around highs and lows (northern hemisphere) appear in this diagram such as to cross a contour in near surface condition (where friction is effective) and to parallel the contour at some elevation owing to the geostrophic effect:

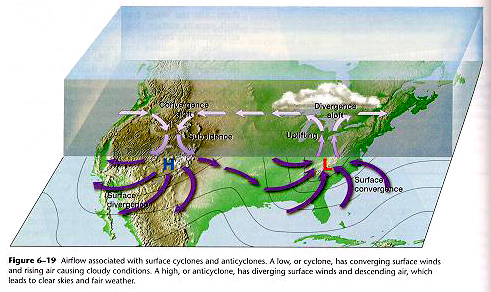


We are now ready to turn to vertical or upward motions of air. This diagram shows the general picture.

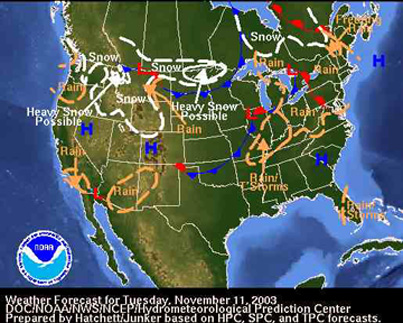


In the diagram, the terms **cyclone** and **anticyclone** are introduced. For a cyclone, the winds circulate counterclockwise around a low. In early case, the air is usually warmer at the surface so it rises in a column such that its winds spiral upward and cool adiabatically. The cyclone is associated with rain-making conditions. An anticyclone is developed where cold air aloft, being heavier and having a higher pressure, descends in spiraling motions to reach the surface as a pressure high.

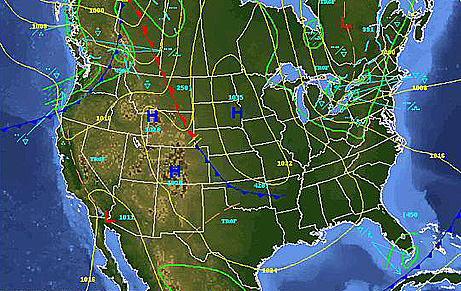
The next diagram, an extension of this idea, establishes a connection at higher altitudes between the low and high air masses that are adjacent. Around the surface low (L), air converges into the lower pressure zones. The rising air reaches some altitude(s) at which the air must then spill outwards as a divergence toward the upper region of the nearby high, where the flow is converging. That air, after moving downward will spread out (diverge) at the surface high locations.



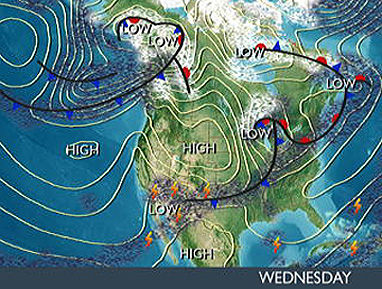
On any given day in a region, such as North America or, more restricted, the United States, surface highs (H) and lows (L) will have developed in various areas of the land mass from differential heating and other causes. Weather forecast maps (treated below) can just show the general areas where these occur, as indicated by positions the H or L's in the center of each mass. This is shown in the next figure for Tuesday, November 11, 2003, the day in which this page was written. Sometimes these weather maps (which may show major isobars at some specified altitude) are depicted such that the precipitation conditions are shown in a general way, either by color-code patches or by contours outlining the extent of the predicted or observed precipitation. In the map, highs are shown in white dashes, lows in brown dashes.



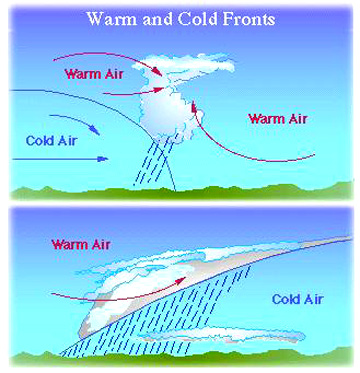
The map below shows Highs and Lows over almost the same area a week prior to the November 11 map. The H's and L's are not in the same position, indicating that these develop in different areas at different times and migrate.



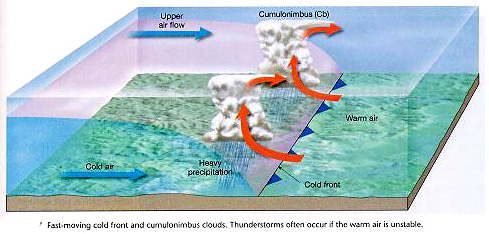
Jumping one day ahead, to November 12, 2003, the location of major highs and lows for all of North America can be shown. The H's and L's for the previous day have moved short distances geographically, mainly eastward.



Both Highs and Lows are mobile and have short life expectancies of days to two weeks (uncommonly longer as is discussed below). In North America, most Highs move from the north and west eastward, but there are other, less common directions of forward motion. Highs and Lows typically grade into each other. The boundary between two contrasting air masses is called a **Front**. It is usually a "sharp" demarcation, with air on either side from the contrasting masses experiencing some mixing in zones of kilometers to tens of kilometers depth. Here is a diagram showing two air masses in proximity with their fronts designated Cold (top panel) where the cold air mass is steep and Warm where the front is more gentle. Note that the cold, heavier air mass, associated with a High, is typically below the lighter warm air.

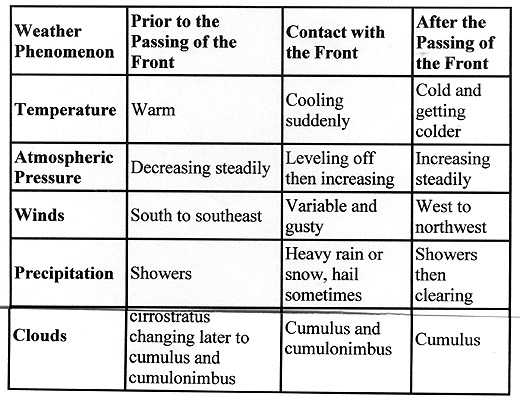


Looking at a Cold Front in more detail:



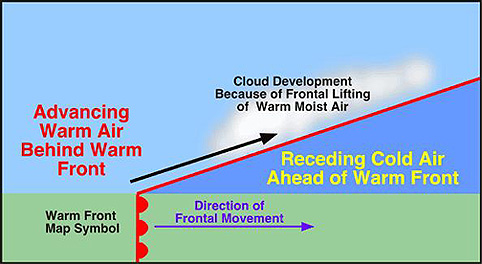
**In front of the usually strong advancing cold air mass, warm air is pushed up and over the steep front, and if laden with moisture, cumulonimbus clouds develop over a rather narrow zone, often bring rainfall initially as thunderstorms. The cold air mass pushes the warm air which falls back or recedes in consort with the advance.**

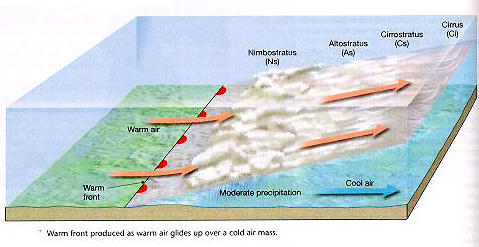
The various conditions associated with a cold front advance have been outlined in this table:

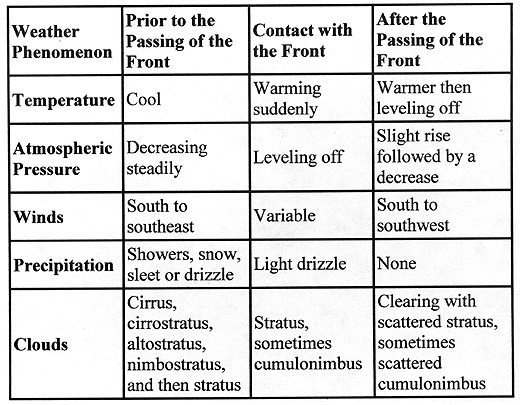


The effects of a cold front passing over any area or weather station are marked by strong storms followed by clearing and dissipation of their trademark conditions in a few days, with warming being the normal result unless another cold front behind the first moves in before the moderation.

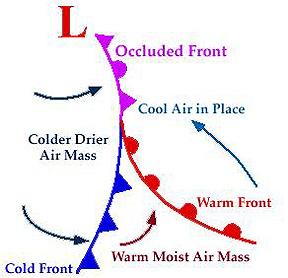
Warm fronts, on the other hand, develop when low pressure, warmer, moist air overtakes a Cold Front. Again, the warm air glides up and over the cold air mass (usually the back end of same). Precipitation is strung out over a much broader area and thick nimbostratus and other stratified cloud types are characteristic. The two diagrams and the table below pertain to Warm Front passage.

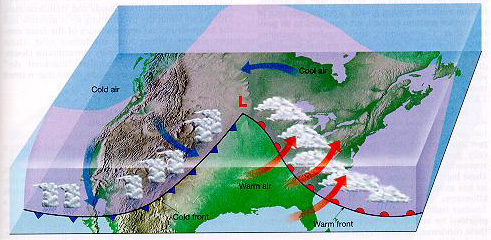




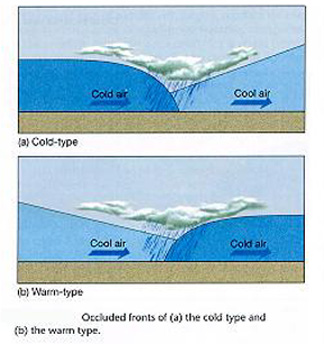


A third situation results when cold air overtakes cool air associated with a cyclonic low in later stages of dissipation. The cold air behind the Cold Front overtakes a Warm Front and forces the relatively warmed (cool) air upwards, causing precipitation. This produces what is known as an Occluded Front, shown in its symbol version and in a perspecive diagram below:

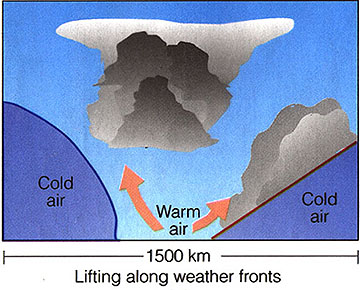




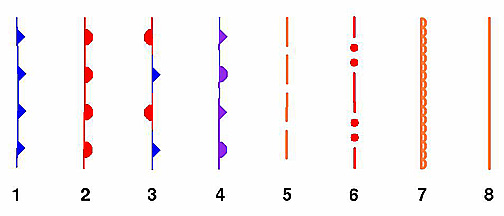
Two types of Occluded Fronts are recognized, as explained in the diagram below:



A special situation is shown in the next diagram. Here warm air trailing advancing cold air is caught within a zone in which a second Cold Front is following the trailing edge of the first Cold Front. The warm air is squeezed upwards forming mostly cumulonimbus clouds that can produce strong thunderstorms:

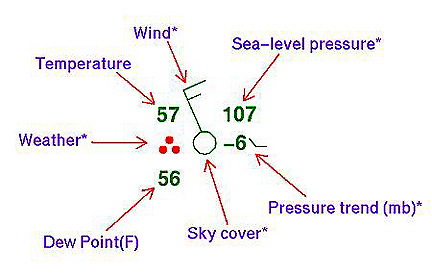


We are now ready to examine how fronts, winds, precipitation, and other weather features are depicted on maps. Some of the symbols used in making weather maps have been introduced in these last groups of illustrations. These are the main symbols for Surface Fronts and related features:

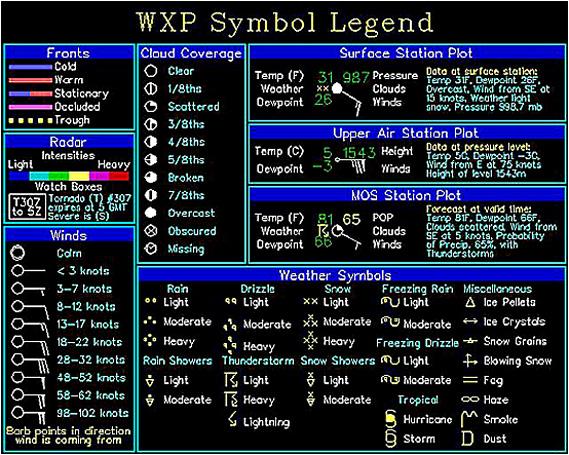


These symbols are identified as follows: 1) Cold Front; 2) Warm Front; 3) Stationary Front; 4) Occluded Front; 5) Trough; 6) Squall Line; 7) Dry Line; 8) Tropical Wave

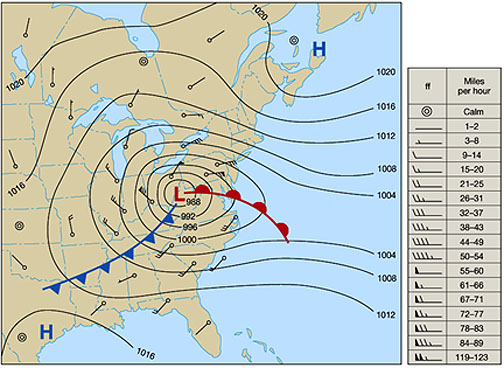
Many maps also show this symbol combination, which is further explained in the chart below:



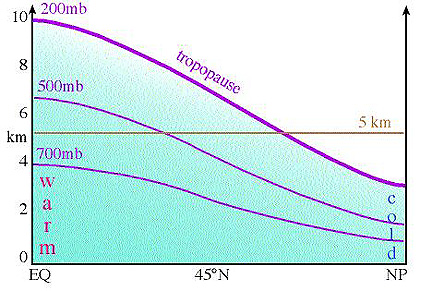
This chart summarizes the main symbols and nomenclature used on some types of weather maps.



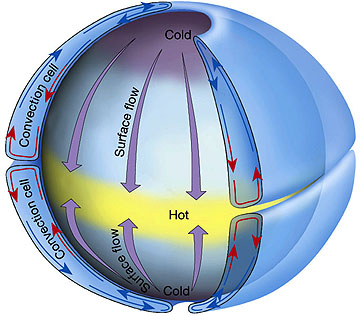
Here is just one example of a weather map that makes use of some of these symbols:



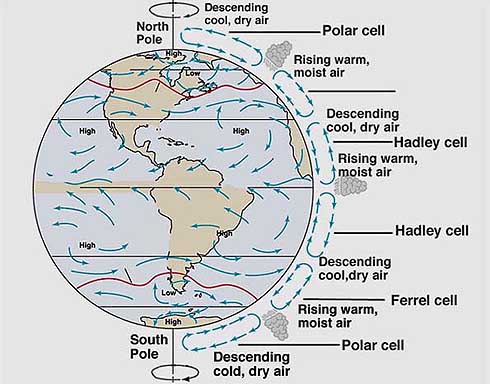
We now have garnered enough background knowledge to talk knowingly about global circulation patterns of the air, which produce both the systematic and the air mass-controlled winds on the surface and aloft and which accounts for rain- or snow-producing precipitation. First, however, we show one general feature of hemispheric air distribution. The tropopause (boundary between troposphere and stratosphere) becomes progressively higher from the poles to the equator, as seen in this diagram. This simply means that cold air at the equator, being heavier, sinks down and brings with it the vertical pressure gradient.



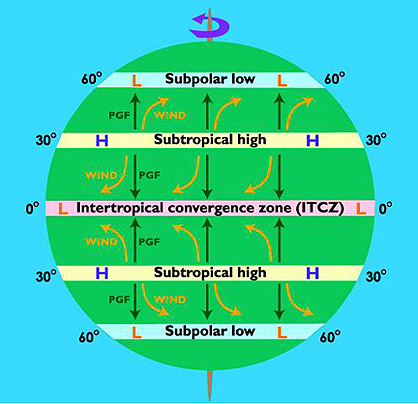
Air, as we have seen, moves under pressure gradients, and is modified by the Coriolis Force and friction, so as to rise, move laterally, and fall depending on its density. This circulation pattern is term a **cell**, or in some instances a **convection cell**. A non-rotating Earth would, in principle, experience at the surface a warming of air in the low latitudes and a cooling of air near the poles. The higher pole pressures drive the air towards the equator. There the warm air rises and cools, and then is driven poleward. This sets up an upper atmosphere flow towards the poles, where the air, now further cooled, sinks. That air is once again driven near the surface back towards the equator. This produces a single circulation cell, indicated in this diagram:



In our real, rotating world the Coriolis Force and other factors cause the single cell to break up into three cells, each with its characteristic circulation pattern. The largest cell, as determined by the area of ground oveer which it operates, is the Hadley Cell. The Ferrel Cell occurs between mid and high latitudes. The smallest cell, is the Polar Cell.



The diagram below this adds some new nomenclature.

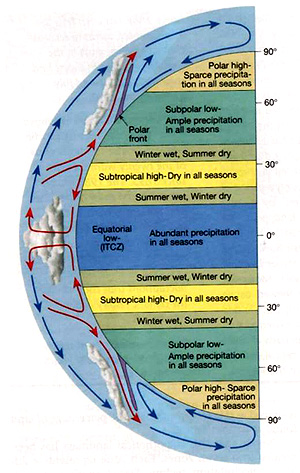


Let examine what happens at each cell zone. At the equator warm air rises and diverges aloft toward each hemisphere's poles. Around 30° N & S latitudes, the air has cooled sufficiently to begin sinking. This colder air forms a high at the surface (the Subtropical High). As the Hadley Cell reaches the surface, it spreads out such that the flow is a return to the equatorial zone to complete the cell movement.

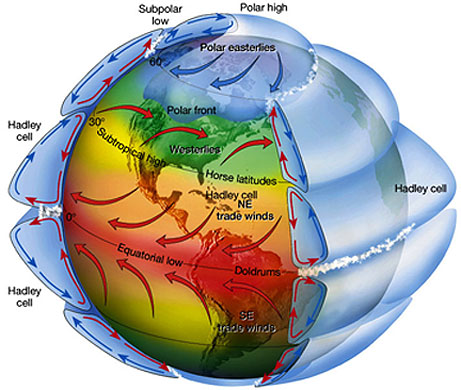
Between 30 and 60° latitudes the Ferrel Cell experiences a reversed flow pattern. Warm (but not hot as in the equatorial zone), moist air around 60°' latitude rises and draws in the cooler 30° air to replace it. The warm air reaching altitude moves towards the equator, cooling as it goes, and then sinks where it encounters air from the Hadley Cell. There, the air from both cells move downward but split (diverge) at the surface to maintain each cell's circulation. The 60° zone is known as the Subpolar Low, since the converging surface air from both cells is warm and hence expanded to be in the low pressure state.

Surface air in the Ferrel Cell flows poleward and again is deflected to the right (north) and left (south). The net effect is for air in this zone in each hemisphere to begin its flow from the west and move eastward. These winds are known as the Westerlies (in naming winds, if a compass direction is stated this means that the wind is flow from the direction stated. By now you should have grasped the principle, and we leave it to you to deduce windflow in the Polar Cells.

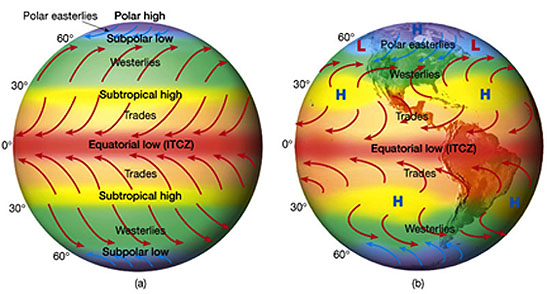
Some of the Subpolar Low air moves northward at altitude and cools progressively. It sinks around the poles, forming a surface High of much colder air. Having no place to go but back towards the poles, the Polar Cell circulation pattern is again like that of the Subtropical pattern. The next diagram combines information from the previous two figures.



As the risk of seeming repetitive, we show this quasi-spherical dimensional representation of the circulation system.



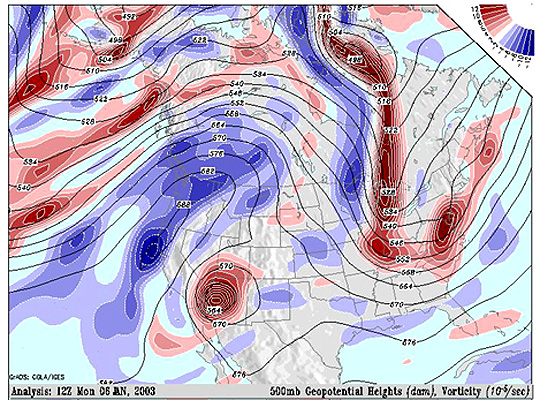
In the last several diagrams there were vector-like arrows that indicate the prevailing directions of surface winds in each cell. This is shown again in the next diagram, after which an explanation ensues:



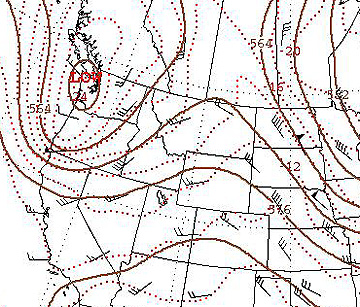
Starting at the equator, the term ITCZ refers to the InterTropical Convergence Zone, which indicates that surface air (windflow) is converging from both hemispheres. The direction of prevailing winds (normal, not influenced by passing regional highs or lows) between the Subtropical Lows and the ITCZ is westward in both hemispheres. The winds from the north deflect right; from the southern hemisphere deflect left, producing the above general directional pattern. These are the Trade Winds, often gentle breezes in the tropical climates, of great help to ships that use sails for propulsion.

(We remind you again that if you are in a location assigned to one of these cells and the wind is not blowing from the directions indicated in the diagram as prevailing, this just means that there is an ongoing passage of air associated with a moving air mass within the cell that has its own circulation patterns, in which as it moves by winds may have several directions. Thus, if you live in any location in the temperate climatic zone - most of the U.S. for example - winds can from time to time shift from the most frequent (prevailing) direction to almost any other direction. Where the writer lives, in Pennsylvania, winds usually are from the northwest, but can from due north, the northeast [big storms], the southwest [often with rain], the south [commonly accompanying tropical air masses], and rarely the southeast.)

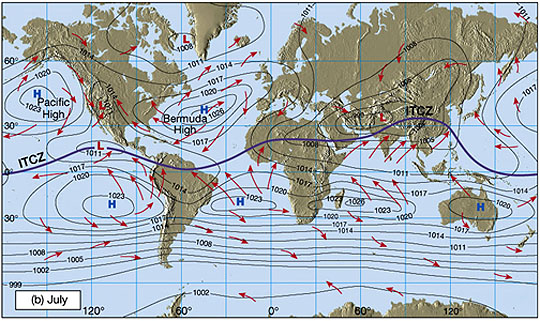
We've implicitly surmised before that winds aloft do not necessary flow in the opposing direction that would be indicated by the cell patterns. Winds at higher altitudes tend to be smoother and more regular, i.e., less turbulent or gusty than surface winds (which are responding also to barriers and areas of stronger differential heating). Below are a map of the United States that shows the isobars (and hence derivied gradients) at 500 (higher) millibars.



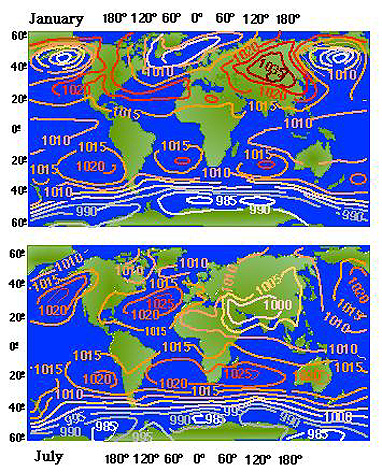
The altitudes reached by the 500 mb pressure surface are not the same from place to place. In this map, the 500 mb altitude lines are by red dots. This next map shows how far above the surface at any point one would go to find the level where the pressure is 500 mb, on this September 19, 2006 date. The contour intervals (4 km) indicate this pressure is at a 24 km altitude in the Pacific Northwest, and reaches down below 12 km elsewhere. Note the broad correspondence of these heights with the pressure contours:



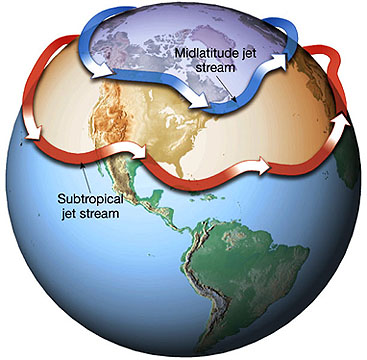
Over some seasonal spans, there is a tendency for the air over the oceans to remain in a fairly constant temperature-pressure range, i.e., a High or Low may persist for weeks. In this illustration, long term air masses over the entire globe are indicated and given identifying names based on some geographic location where they often originate or are found. The Bermuda and Pacific Highs are two such air masses. Although this map covers the period between January and July, the highs are especially effective in the warmer months and tend to influence and even control air mass directions. In the Atlantic, the Bermuda High tends to weaken in late Summer and Fall, as hurricanes develop and move toward this High (which if still coherent, may deflect and thus determine the hurricane path).



These two maps show the generalized pressure centers across the globe in January and in July



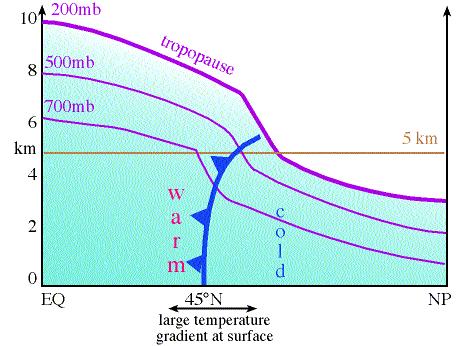
Finally in this survey of circulation patterns we call attention to the oft-mentioned **Jet Streams** you hear about on the Weather News. These function as steering currents for air masses and as zonal boundaries for sharp differences in temperatue. The jets are cited as major factors in the type of weather predicted for now and the next few days. Jets are something like "rivers of air" found at high altitudes and noted for their high speeds. They develop just below the Tropopause. In the Northern Hemisphere, there are two such streams: the Mid-Latitude Jet - which is the one usually affect weather in the U.S., Europe and Asia, and the Subtropical Jet. Typical positions of the two are shown in this diagram



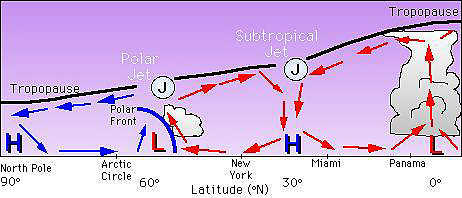
The Jet Stream affecting the U.S. moves up and down across the continent. When it is farther north, say in Canada, the weather to its south tends to be mild or at least less cold. When the stream, which meanders, swings south until well within the U.S., especially in winter, very cold, often harsh weather prevails at the surface on the northern side. This diagram shows two typical positions at the height of Summer and of Winter.



Northern Jet streams form in the upper troposphere at the boundaries between cold, usually Arctic or Polar Air Masses and warmer air to the south. Conditions for formation include a strong temperature gradient at the surface which induces a steepening of the vertical isobaric gradient as shown in this figure. Air concentrates along the upper boundary of the steepened pressure front and is then moved along by the Coriolis force. This diagram shows that condition.



This last figure shows this idea in a somewhat different way. The Mid-Latitude (also called Polar) Jet occurs when Polar or Arctic air encounters warm air. The Subtropical Jet develops at the top of converging air where the Hadley and Ferrel Cells meet.



Having now been enlightened by these ideas concerning general air mass behavior, you are ready to consider more localized phenomena such as rainfall, and thunderstorms, tornadoes, and hurricanes, and at the close the nature and effects of different climates.

avigation image map

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